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Structural Origin of Sinjar Anticline, NW Iraq

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Abstract

The Sinjar anticline is a double plunging, trending almost E-W in the northwestern part of Iraq. It extends in Syria for about 42 km, whereas in Iraq, its length is about 91 km, and the width is about 31 km. The northern limb (45˚ - 80˚) is steeper than the southern limb (15˚ - 25˚), with average plunges dip of 35˚ and axial plane dipping of 47.5˚ southwards. The exposed rocks in the anticline range in age from Upper Cretaceous, represented by the Shiranish Formation, to Upper Miocene, represented by the Injana Formation. Google Earth image was used to calculate structural data, which were used to indicate the structural origin of the Sinjar anticline. This was achieved by calculating the Aspect Ratio (AR), Fold Symmetry Index (IFS or IFS), and length of the mountain front (FS). Accordingly, it was found that the structural origin of the Sinjar anticline is a fault-bend fold.

Keywords

Aspect Ratio, Fold Symmetry Index, Mountain Front Length, Sinjar Anticline, Iraq

1. Introduction

The Sinjar anticline is an outstanding structural and geomorphological feature in the northwestern part of Iraq; the anticline extends in Syria for about 42 km, whereas in Iraq, its length is about 91 km totaling about 133 km with a width of about 31 km. (**Figure 1**). The anticline is within the Low Folded Zone (LFZ) of Iraq. The zone is a part of the Zagros Fold-Thrust Belt (ZFTB). This belt, however, is a part of the Zagros Foreland Basin, which covers large parts of the Iraqi territory and is developed due to the collision of the Arabian and Eurasian plates in the convergent form [1] [2] [3]. The anticlines raise in between a wide and gently rolling plain on its northern and southern sides (**Figure 1**). In the north, the plain is called Rabi'a Plain, which has an elevation that ranges between

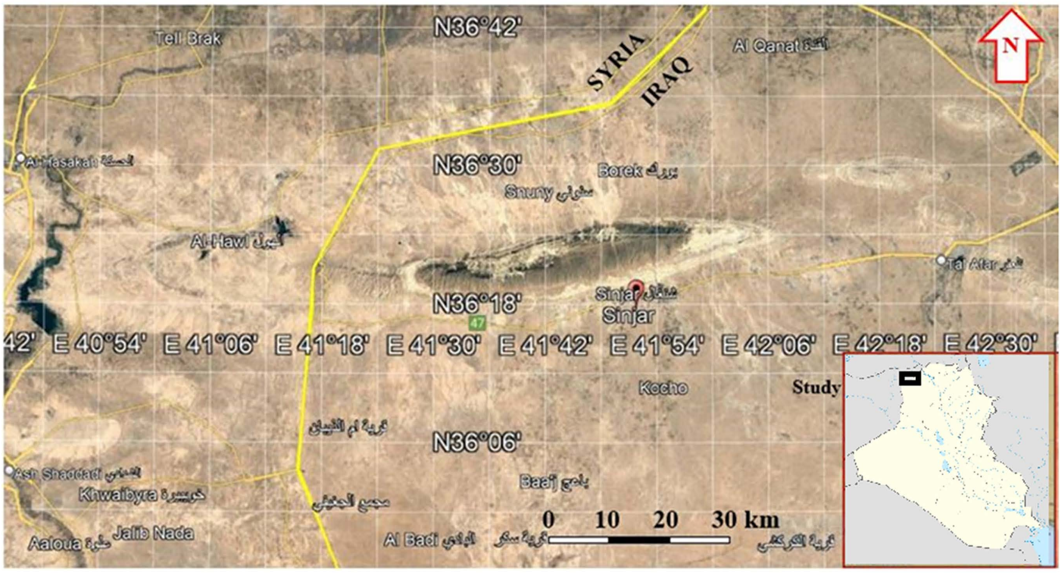

Figure 1. Google Earth image showing the location of the studied area.

(460 - 515) m (a.s.l.), whereas in the south, it is called Al-Jazira Plain, which has an elevation that ranges between (380 - 440) m (a.s.l.). The highest peak in Sinjar Mountain is 1421 m (a.s.l.), on the Iraqi side; it is located north of Sinjar town along the southern flank of the mountain.

Different geological studies have been carried out; however, structural and geomorphological works are very rare. Al-Daghastani [4] has used remote sensing techniques to study the alluvial fans of the Sinjar anticline, and he furnished detailed geomorphological data about the alluvial fans. Al-Daghastani *et al.* [5] have used remote sensing data to map the developed alluvial fans along the Sinjar anticline in seek of water harvesting. Accordingly, they have prepared a detailed geomorphological map. Moreover, they have classified and mapped the existing landforms in the studied area. Al-Daghastani and Al-Dewachi [6] have studied the alluvial fans along the northern side of the Sinjar anticline within Rabi'a Plain. They attributed the developed stages of the alluvial fans to Neotectonic movements. Sissakian [7] studied the developed alluvial fans along both sides of the Sinjar anticline. He has recognized the five stages of fans and concluded that the five stages are developed due to Neotectonic movements. Fouad [8] has conducted a tectonic study for the whole Low Folded Zone in which the Sinjar anticline is present. He concluded that the anticline is a structural high above an earlier structural low, indicating an inverted graben. He also conducted an analysis of tectono-stratigraphic sequences in the Mosul region, and consequently concluded that the folds in the region of the Sinjar anticline had formed in two episodes; during the early Campanian-Maastrichtian episode of extension and rift formation, followed by Pliocene-Pleistocene episode of compression and fold formation. Therefore, the Cretaceous rocks of the Shiranish Formation are exposed in the Sinjar anticline. Sissakian *et al.* [9] have conducted a Neotectonic and geomorphological study of the Sinjar anticline. They have constructed a

Neotectonic map and accordingly have calculated the rates of upwards and downwards movement. They also have recognized different morphological and structural forms, which indicate that the Sinjar anticline is laterally growing. Baghbanan *et al.* [10] also studied the Khalfani Anticline, Coastal Fars, and Zagros Fold-Thrust Belt and indicated the type of the fold using the same opinion.

The aim of this study is to indicate the structural origin of the Sinjar anticline and to compare the acquired data about the origin with the previously existing data about the structural origin of the Sinjar anticline. The achieved data depend on the calculated data about different structural and geomorphological aspects.

2. Materials and Methods

As materials, the following data were used to fulfill the aim of the current study: Geological and topographical maps, Google Earth images, and relevant published articles.

The main used method in the current study is the opinions of Burberry *et al.* [11] and Burberry [12] were adopted to calculate the structural data which were used to indicate the structural origin of the Sinjar anticline.

The following parameters were calculated: the length and width were calculated using a Google Earth image (**Figure 2**). The Aspect Ratio (AR), Fold Symmetry Index (IFS), and Mountain Front Sinuosity or Fold Front Sinuosity (Smf) (**Figure 3(a)**) of the Sinjar anticline were calculated using the following equations:

The Fold Symmetry Index (IFS) is calculated using the following equation [11]:

$$\text{IFS} = S/(W/2) \tag{1}$$

where: S is the width of the forelimb, and W is the width of the fold (**Figure 2**).

The Aspect Ratio (AR) is calculated using the following equation [11]:

$$\text{AR} = L/W \tag{2}$$

where: L is the length of the fold, and W is the width of the fold (**Figure 2**).

The Fold Front Sinuosity (Smf) is calculated using the following equation [13]:

$$\text{Smf} = Lmf/Ls \tag{3}$$

where: Lmf is the length of the mountain front (FS) along the foot of the mountain at the pronounced break in slope, and Ls is the straight-line length of the mountain front (L in **Figure 2**).

The Relative age of the folds can be estimated following the opinion of Burberry *et al.* [11] by imposing the Smf (FFS) value versus the distance from the Main Zagros Thrust Fault.

The dip amounts of both limbs and plunges of the Sinjar anticline are measured from Google Earth images using the following equation

$$\tan \varnothing = H/D \tag{4}$$

where: H is the height difference between the top and bottom points along a certain bedding plane on the Google Earth image (Points A and B in **Figure 3(b)**),

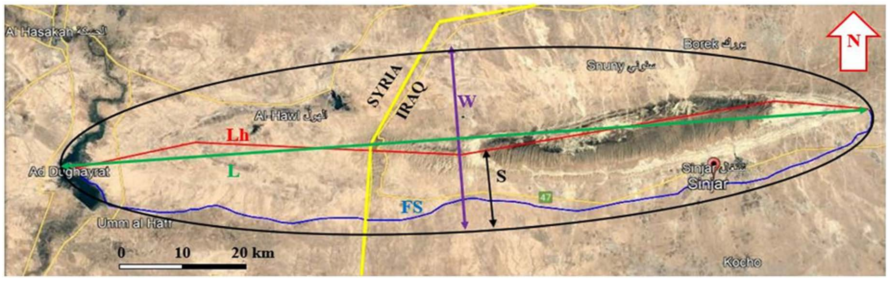

Figure 2. Google Earth images showing the measured parameters.

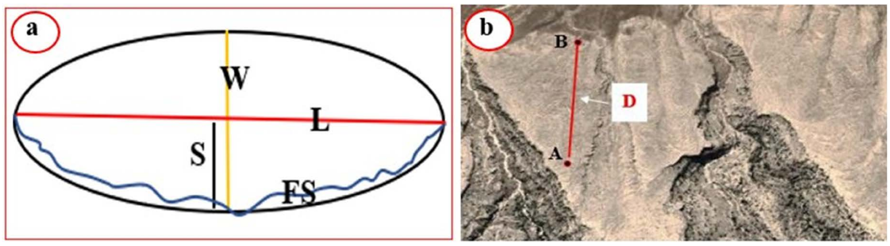

Figure 3. (a) Representation of the measured parameters; (b) presentation of the dip measurement on the southern limb of the Sinjar anticline (Google Earth image).

where the dip amount was calculated, accordingly, the heights of both points were measured,

D is the distance between the two measured points, also measured from the scale of the Google Earth image (Figure 3(b)), then Ø will be the dip angle.

The averages of dip amount of both limbs, plunges, and axial plane are presented in Table 1.

3. Geology of the Sinjar Anticline

The geology of the Sinjar anticline is briefed hereinafter based on [8] [14] [15].

3.1. Geomorphology

The main and widely developed geomorphological form is the alluvial fans [4] [5] [6] [15]. The fans are well-developed on both limbs, especially in the Iraqi part of the anticline. Five stages of the fans are well recognized, the apex of each stage indicates Neotectonic activity [16]. Flat irons, anticlinal ridges, and bajada are also well-developed on both limbs of the anticline. Different types of valleys were recognized during the interpretation of satellite images, such as fork-shaped, axial, radial, and inclined, they all indicate lateral growth of the anticline [17] [18]. Abandoned alluvial fans and wind gaps also were recognized during the interpretation of satellite images, besides, the wale-back shape of the anticline, they also indicate lateral growth of the anticline [19].

3.2. Stratigraphy

The exposed formations in the Sinjar anticline are presented in Figure 4, based on Sissakian and Al-Jiboury [14]. The oldest rocks are of Upper Cretaceous age;

Table 1. Measured geomorphological indices and structural elements along the Sinjar anticline.

Length (km)		W (km)	S (km)	FS (km)	AR	FSI (IS)	Smf (FFS)	Average dip amounts (˚)			
Normal	Hinge							Limb		Plunge	Axial surface
L	L h							N	S		
133	137.5	31.25	13.5	141	4.26	0.86	1.06	65	20	35	47.5 S

Formation	Age	Thick. (m)	General description
Injana	Late Miocene	300 – 400	Sandstone interbedded with siltstone and claystone in rhythmic cycles, all rocks are reddish-brown in color
Fatha	Middle Miocene	550 – 630	Green marl interbedded with limestone and gypsum in rhythmic cycles, in the upper cycles, reddish brown claystone occurs.
Jeribe		100 – 125	Well bedded greyish white limestone
Dhiban	Early Miocene	5 – 100	Mainly limestone with rare limestone
Serikagni		65 – 300	Well bedded white limestone with some marl intercalations
Avanah	Middle Eocene	85	Marly limestone interbedded with marl
Jaddala		500 – 550	Marl interbedded with marly limestone
Sinjar	Early Eocene-Late Paleocene	170	Well bedded, white, and very hard limestone
Aaliji		50	Shale and marl
Shiranish	Late Cretaceous	565 (exposed)	Bluish green, papery marl, in the upper part well bedded greyish white limestone in the lower part

Figure 4. Tentative columnar section of the exposed formations in the Sinjar anticline. The red lines represent unconformities.

belong to the Shiranish Formation, whereas the youngest rocks are of Upper Miocene; belong to the Injana Formation.

3.3. Tectonics and Structural Geology

The Sinjar anticline is located within the Low Folded Zone of Iraq; the zone is part of the Outer Platform, which belongs to the Arabian Plate [3]. The Sinjar anticline and other folds in the region are developed due to the collision of the Arabian and Eurasian plates [1] [3] [8] [20]. The Sinjar anticline is 133 km long and 31 km wide, trending almost E-W. A normal fault trending E-W runs along the northern limb of the anticline; many other small faults occur too. Along the southern limb a low amplitude anticline occurs, it is developed within the Sinjar Formation with a length of about 15 km and separated from the main axis of the Sinjar anticline with a shallow syncline

4. Results

The following results were achieved from the calculated and indicated data based on the interpretation of satellite images; as the Sinjar anticline is concerned.

4.1. Aspect Ratio (AR)

The acquired data of the aspect ratio (**Table 1**) were plotted versus the hinge length of the Sinjar anticline (**Figure 5**) to indicate the structural origin of the anticline. Following the opinion of Burberry *et al.* [11], the Sinjar anticline is close to Fold-Bend Fold (**Figure 5**).

4.2. Fold Symmetry Index (IFS)

The acquired data of the fold symmetry index (**Table 1**) were plotted versus the length of the Sinjar anticline (**Figure 6**) to indicate the structural origin of the anticline. Following the opinion of Burberry *et al.* [11], the Sinjar anticline is close to Fold-Bend Fold (**Figure 6**).

4.3. Mountain Front Sinuosity Index (Smf) and Relative Fold Age

This index represents the balance between erosion and tectonics [21]. The erosion tends to produce a straight mountain front coincident with an active range-bounding fault. Therefore, as large the difference between the length of the anticline and the mountain front (**Figure 2** and **Figure 3**); as much the erosion extensive is. Accordingly, the Smf value is large. In the Sinjar anticline, the acquired value of Smf is 1.06 (**Table 1**), which means extensive erosion.

The Smf or FFS value (1.06, **Table 1**) of the Sinjar anticline was imposed versus the distance of the anticline from the Main Zagros Fault (**Figure 7**), which is about 280 km [22] to indicate the relative age of the fold. The result showed that the fold is relatively young.

4.4. Shape of the Anticline

To indicate the shape of the anticline, the opinion of Fluety [23] was adopted. The average amount of both plunges and the axial plane angle of the Sinjar anticline were imposed on the diagram of Fleuty [22] (**Figure 8**). Accordingly, it was found that the Sinjar anticline is moderately plunging with moderate dipping axial plane.

5. Discussion

According to Fouad [8] [20] the development of the Sinjar anticline in the Low Folded Zone as an outstanding structural and geomorphological form is due to

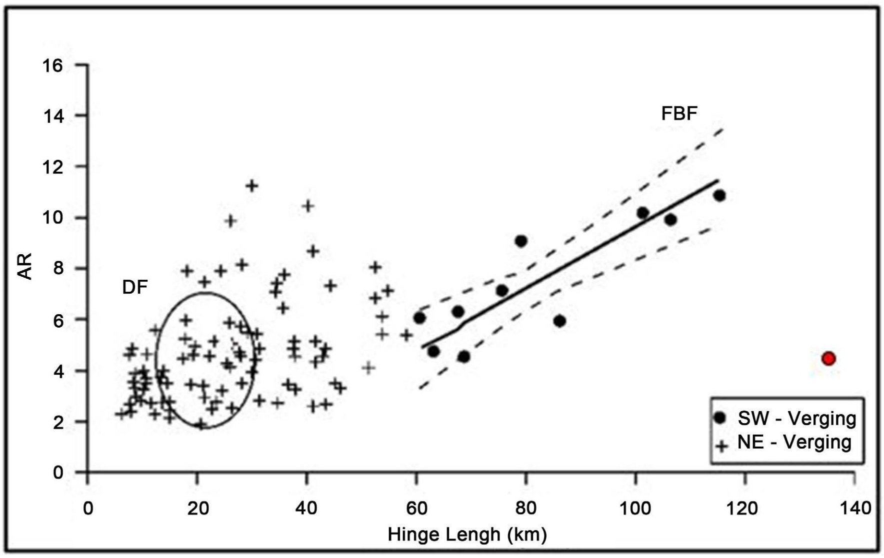

Figure 5. Aspect Ratio (AR) versus the hinge length diagram. The black dots are from Burberry *et al.* [9], the red dot represents Sinjar anticline. DF = Detachment fold, FBF = fault-bend fold.

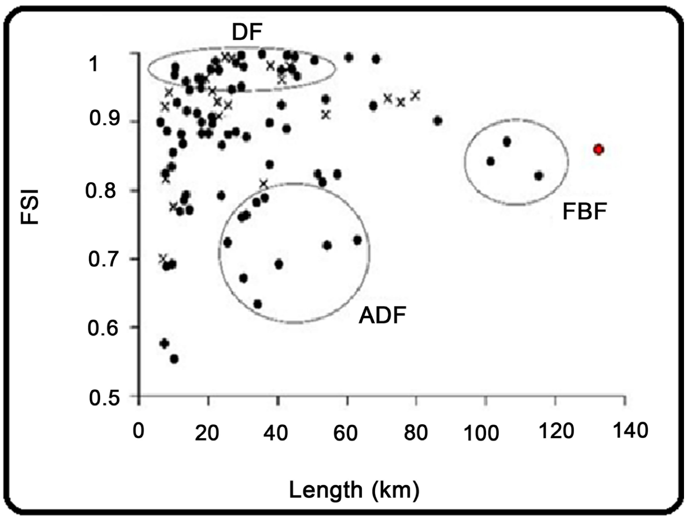

Figure 6. Fold Symmetry index versus the length diagram. The black dots are from Burberry *et al.* [9], the red dot represents Sinjar anticline. DF = Detachment fold, FBF = fault-bend fold, ADF = Asymmetric Detachment Fold.

the origin of the anticline, which is an inverted graben. The deformation of the anticline (presence of a parasitic long fold along the southern limb and a long axial fault) is due to the inversion process, besides the lateral growth of the fold [9] as indicated by different geomorphological and structural forms like different shaped valleys, abandoned alluvial fans, en-echelon folds, etc. Moreover, the exposure of rocks as old as the Upper Cretaceous in the Neogene dominant rocks domain is another indication of the inversion; otherwise, no Cretaceous rocks can be exposed.

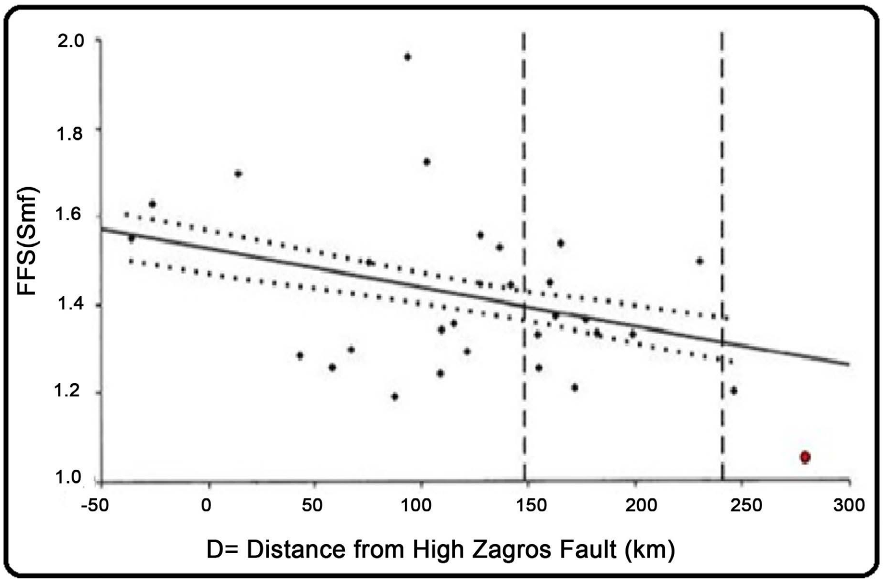

Figure 7. Relative age of fold structures within the Zagros Simply Folded Belt (From [9]). The red dot represents Sinjar anticline

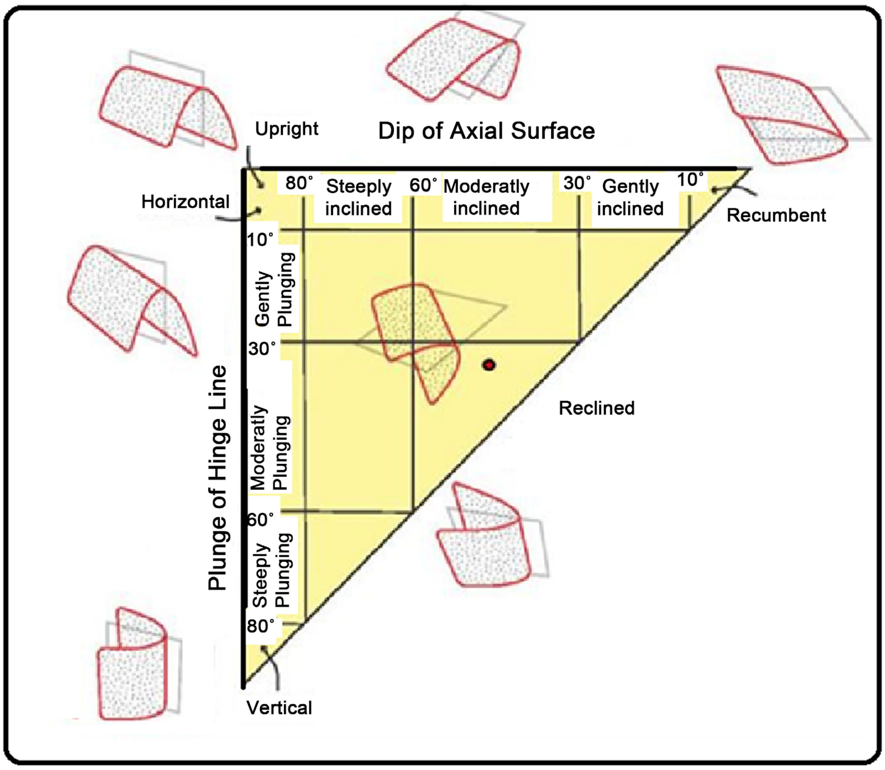

Figure 8. Classification of anticlines according to Fleuty [21]. The red dot represents the Sinjar anticline

Since the Sinjar anticline has grown on an inverted graben [8] [20], then there should be two faults on both sides of the graben. Accordingly, the indicated structural origin as "Fault-Bend Fold" based on the indicated Aspect Ratio and Fold Symmetry Index [11] coincides with the proven origin of the Sinjar anticline. The high amplitude of the anticline as compared to the neighboring folds is another indication that the origin of the Sinjar anticline is a Fault-Bend Fold. Such a case is also confirmed [11] from the Simply Folded Belt in Iran, which comprises the Low Folded Zone in Iraq.

According to Burberry *et al.* [11], the "relative age of fold structures within the Zagros Simply Folded Belt, decreases from the hinterland towards the foreland (**Figure 7**). Anomalously old folds are located close to the thrust faults implying the interaction of footwall collapse and subsequent serial folding as the deformation front migrates to the SW". **Figure 7** shows that the Sinjar anticline is relatively younger than those developed in Iran. This is because the folds age decreases from the hinterland (in Iran) towards the foreland (in Iraq). Therefore, old folds are located close to the thrust faults indicating the interaction of footwall collapse and subsequent serial folding as the deformation front migrates towards the southwest.

The structural shape of the Sinjar anticline based on the classification of Fluety [23] is a fold with the moderately inclined axial surface (plane) and moderately plunging anticline (**Figure 7**).

6. Conclusion

The main aim of the current research is to indicate the structural origin (type of folding) of folds using geomorphological and structural forms, especially when no seismic data are available. Therefore, we used the opinion of Burberry [11] to indicate the origin of the Sinjar anticline and found it is a "Fault-Bend Fold". This is based on the calculated Aspect Ratio and Fold Symmetry Index. Moreover, the high amplitude of the anticline and exposed Cretaceous rocks in the core of the anticline are also good indications of the origin. However, the last mentioned two aspects are related to the inverted graben case, which is another indication of the origin of the anticline. As the relative age of the anticline is concerned, then it is relatively younger as compared with those developed in the hinterland within the Simply Fold Belt in Iran. The structural form of the anticline is defined as a fold with a moderately inclined axial surface (plane) with a moderate plunge.

Authors' Contribution

The main text is written by Mr. Varoujan Sissakian. Dr. Nadhir Al-Ansari has reviewed and amended the article using his constructive comments. The final version was discussed between both authors using the Zoom application.

Data Availability

Both authors declare that all used data are presented in the text.

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Conflicts of Interest

Both authors declare that there is no conflict of interest as the current article is considered.

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Abbreviations

All used abbreviations are defined before their first usage in the text. However, a.s.l. means: Above sea level.